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REAL –TIME DISPATCHING MODELLING FOR TRUCKS WITH DIFFERENT CAPACITIES IN OPEN PIT MINES

MODELOWANIE W CZASIE RZECZYWISTYM PRZEWOZÓW CIĘŻARÓWEK O RÓŻNEJ ŁADOWNOŚCI W KOPALNI ODKRYWKOWEJ

Application of fully automated systems for truck dispatching plays a major role in decreasing the transportation costs which often represent the majority of costs spent on open pit mining. Consequently, the application of a truck dispatching system has become fundamentally important in most of the world's open pit mines. Recent experiences indicate that by decreasing a truck's travelling time and the associated waiting time of its associated shovel then due to the application of a truck dispatching system the rate of production will be considerably improved. Computer-based truck dispatching systems using algorithms, advanced and accurate software are examples of these innovations. Developing an algorithm of a computer-based program appropriated to a specific mine's conditions is considered as one of the most important activities in connection with computer-based dispatching in open pit mines. In this paper the changing trend of programming and dispatching control algorithms and automation conditions will be discussed. Furthermore, since the transportation fleet of most mines use trucks with different capacities, innovative methods, operational optimisation techniques and the best possible methods for developing the required algorithm for real-time dispatching are selected by conducting research on mathematical-based planning methods. Finally, a real-time dispatching model compatible with the requirement of trucks with different capacities is developed by using two techniques of flow networks and integer programming.

Keywords: Transportation; Truck Dispatching and Allocation; Optimisation of Mines' Transportation; Integer Programming

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Zastosowanie w pełni zautomatyzowanych systemów dysponowania przewozami ciężarówek w poważny sposób przyczynia się do zmniejszenia kosztów transportu, które częstokroć mają poważny udział w kosztach funkcjonowania kopalni odkrywkowych. Dlatego też zastosowanie systemu dysponowania transportem ma kluczowe znaczenie w kopalniach odkrywkowych na świecie. Niedawne doświadczenia wskazują, że poprzez zmniejszenie czasu przejazdu ciężarówek oraz zmniejszenie czasu oczekiwania dzięki zastosowaniu systemu dysponowania przewozami możliwe jest znaczne podniesienie poziomu produkcji. Wspomagany komputerowo system dysponowania przewozami wykorzystujący odpowiednie algorytmy a także zaawansowane oprogramowanie stanowią przykłady nowoczesnych rozwiązań w tej dziedzinie. Opracowanie algorytmu komputerowego dostosowanego do konkretnych warunków panujących w danej kopalni odkrywkowej jest jedną z kluczowych czynności dla uruchomienia komputerowego systemu dysponowania przewozami ciężarówek w kopalni. W artykule przedstawiono zmieniające się trendy w zakresie programowania, algorytmów sterowania przewozami i automatyzacji. Ponadto, ponieważ większość kopalni odkrywkowych wykorzystuje ciężarówki o różnej ładowności, wybrano najlepsze i najnowocześniejsze metody i techniki optymalizacji oraz najskuteczniejsze metody opracowywania algorytmów wspomagających systemy dysponowania przejazdami ciężarówek w czasie rzeczywistym, wybrano je w oparciu o metody planowania wykorzystujące aparat matematyczny. W części końcowej zaprezentowano model dysponowania przewozami w czasie rzeczywistym kompatybilny z wymogiem zastosowania ciężarówek o różnej ładowności, opracowany w oparciu o metody sieci przepływowych i programowania binarnego.

Słowa kluczowe: transport, dysponowanie przewozami, optymalizacja transportu w kopalni, programowanie binarne

1. Introduction

Due to the recent progress of all industries and their needs for raw materials, mining must be improved in parallel with other industries and adopt better technology to enhance the industry both technically and economically. Optimisation models are among the most useful methods to attain such objectives. Such models will improve mining technically and are of a great importance to challenge the economical issues of the industry, (Aghajani Bazzazi et al., 2009; Topuz & Luo, 1987; White & Olson, 1986).

Taking into consideration the downward movement of mining grades and existing reserves and increasing production expenses, open pit mines must try to optimise the productivity through utilising automation of operations. To do this, the decisions must be made in a timely manner. So, obtaining information adequately on each individual element of a mine is paramount. Proper and real-time application of such information creates the possibility of employing a dynamic programming system which is sensitive to market conditions, condition of equipment, grade changes, geometry and hardness of ores achievement of production objectives with expected efficiency can become feasible. If real-time information is available through monitoring, positioning and communication with equipment, then an active optimisation can be incorporated into the programming (ČECH, 2010; Peck & Gray, 1995).

The purpose of incorporating different stages of mineral programming is the positive impact that can be gained when examining the Net Present Value resulting in cash flows that can be maximised during the mine's lifetime. During programming of mining, initially all long-term planning will be developed based on geological information and economical parameters through which an annual perspective of the mine for maximisation of Net Present Value is provided. Due to the application of optimised long-term plans, monthly, weekly or daily short-term plans can be implemented and managed for developing and expanding the degree of mining within a limited period of time and according to this short-term plan, the material transferring is undertaken in connection with the mining operation. Currently, Shovel-Truck Systems are generally considered to be the best system for material transferring during open pit mining operations (Arnold & White, 1983).

Truck cycle patterns will be generated in order to identify the mine road's network rout which includes the start and finish of the loading points and the its various destinations such as processing plant and/or dump locations.

During the operation stages, each individual truck is allowed to be loaded by dedicated loading machine or it may be sent to several different loading machines. Allocation of a truck to several loading machines is certainly more efficient and causes the production to be improved in a Shovel-Truck System. Finding the allocation of an optimised and instantaneous truck for transferring materials according to important parameters and their effects on the success of a short-term plan is considered as the main issue (Beaudoin, 1977).

Whenever materials transferring during mining operations are considered as the main part of the operation, a Shovel-Truck System will generally be the most efficient means of transfer. Throughout the operation, the truck departs from a starting point towards a specified destination. The starting point is a place where a truck is loaded by different materials therein. A shovel or a loading machine location may be considered as a starting point. A destination is a place a truck is unloaded therein. A crusher or a dumping place can be considered as a final destination (Bonates & Lizotte, 1988).

The number of trucks needed for an operation as well as the allocation of trucks will be determined according to the short-term plans for materials transferring on a daily basis. In principle, the number of required and allocated trucks must be designated in such a way that given the period of the short-term plan and other dependant factors such as the truck's capacity, length of route, production objective and real-time truck dispatching, the number of trucks required for achieving mining objectives is as minimal as possible (Dagdelen, 1996; Dyer & Jacobsen, 2007).

Since more than 50% of mining costs are generally allocated to loading and transportation in open pit mines (Akbari et al., 2009; Oraee & Goodarzi, 2007), then decreasing by a small percentage these costs will give rise to a considerable saving for the operation (Micholopulos & Panagiotou, 2001; Xing & Sun, 2007). Therefore, developing the appropriate models for optimised utilisation of equipment and decreasing operational costs of mine are inevitable. Dispatching models are among such models that cause the transportation system to be optimised and productivity of mines to be improved (Bascetin, 2004; Jian-hong et al., 2008).

The first step for establishing algorithms through which a complicated situation such as mineral transferring may be controlled will be a mathematical model by which the process of transportation technology from extraction point to mill could be described. A real-time dispatching model compatible with specifications of the trucks with different capacities is developed by using two techniques namely Network Theory and Integer Programming.

2. Application of Dispatching in Open Pit Mines

The truck dispatching issue is not peculiar to the mining industry. In fact, many of the industries using a transportation fleet are involved with such a problem. The truck dispatching main issue needs to answer the question where does the truck have to go after it is unloaded? To answer this question, first of all it is necessary that given the specified objective, the best destination is determined for the truck. Of course, truck dispatching in the mine is not complicated as compared to other industries and sometimes there is only one option for truck dispatching. Transportation systems in the mines are often closed systems and then loading and discharging points remained unchanged for a long periods. Meanwhile, the shuttle distance is short in comparison with the shift time period and the rate of demand is high at each individual point (Alarie & Gamache, 2002).

The truck dispatching issue is amongst the primary matters that has to be taken into consideration to improve a mines' productivity. Two major outcomes follow in all dispatching systems these are: To maximise the application of the shovel (to minimise the interruption time of the shovel) and to maximise the application of the trucks (to minimise waiting time of trucks i.e., queuing). A secondary outcome would be to maximise the loading capacities for trucks along different routes to ensure the operation reaches an accurate and required rate of production in each period (Temeng et al., 1997).

By complicating the conditions of decision making and achieving the required objectives is becoming more difficult. For this reason and given the automation process currently used in the mines, the previous models and algorithms are not appropriate for planning and controlling the haulage system (Cross & Williamson, 1969; Elbrond & Soumis, 1987). Therefore, some methods have been initiated to attempt to achieve the required objectives. In this regard, researchers have developed various models for optimization of loading and transportation. Optimisation models have been emerging since the 1970s and have been successfully implemented since the 1980s. However, by 1997, a target function was considered in all optimisation models. Maximisation of profit, minimisation of costs and minimisation of distance are typical of such constraints which can be solved using the linear programming technique. To succeed in reaching only one of these goals is one of the disadvantages of this method. In other words, without consideration of the conditions of a problem (in terms of objectives which are of little priority) optimisation as an objective is only met (Chung et al., 2005). As a result, the structure of dispatching models has been gradually evolving and in comparison with the status they have had in the past have evolved from a single-stage form into multi-stages forms and are developing towards real-time dispatching algorithms (Jian-hong et al., 2008).

Multi-stage dispatching models (two or three stages) usually consist of two main parts: the first part is usually a linear programming model or a non-linear programming model employed to determine the production volume per shift or per hour in compliance with the objectives of the operations short-term plans. The second part uses innovative methods and/or mathematical programming to develop a real-time dispatching algorithm and is intended for dynamic allocation of trucks to shovels according to the optimised solving of the first part (Jian-hong et al., 2008; Xi & Yegulap, 1994).

In recent years, some multi-stage dispatching models have been developed in this regard. In 1989, Lizotte & his colleagues initiated the application of comparative innovative methods in the first stage for the allocation of trucks based on solving a linear programming model. In 1990, and for the purpose of allocating trucks based on solving a linear programming model, Zhang and his colleagues initiated the use of an innovative method in the first stage in order to minimise the saturation degree of loading point of trucks. In 1990, for the purpose of minimising a truck's waiting time for an allocated shovel, Soumis and Elbrond initiated the use of the allocation method in the first stage for allocating trucks based on solving a non-linear programming model. In 1993, White and his colleagues initiated the application of dynamic programming in the first stage for allocating the 'Best Truck' to the most demanding route (or shovel) based on solving a linear programming model. In 1994, Xi and Yegulap initiated the application of a deviation programming model based on optimised solving of a linear programming model. In 1997 and 1998, Temeng and his colleagues developed the real-time dispatching model in which a transportation-based method has been applied to proper allocation of trucks based on solving an ideal model. In 2000, Kolonjia generated a haulage system with respect to the effects on a crusher system newly installed in a mine on establishment of a Shovel-Truck System and so developed a simulation model for the transportation system of an open pit mine. In 2002, inspired by natural guidance existing in our insects' society; Bissiri applied a working sequence mechanism of Shovel-Truck System. The results of researches have indicated that depending on the existing mining operation, positive results of dispatching due to application of the combination of rules is more likely (Chung et al., 2005).

3. Allocating a Truck to a Shovel

Trucks are allocated to the shovels in two ways: Fixed allocation and Flexible allocation (Ataeepour and Baafi, 1999; Sadri et all., 2008). Below both methods are discussed in detail:

3.1. Fixed Allocation

In this method, a truck is dedicated to a special shovel and this condition will remained unchanged until the end of the shift. The numbers of trucks dedicated to each shovel will be fixed and will never be changed throughout the shift. Each individual truck is allowed to be loaded by a specified shovel and once given to its dedicated load (mineral or waste) is then dispatched to a discharging point (crusher, ore or waste dump). In other words, it can be asserted that a fixed allocation method is a static method for truck allocation and while the allocation program remains unchanged, it will be continued. Conventional methods in which queuing theory principles are used along with innovative programming are amongst the different methods applied for truck allocation. All such methods intend to determine the optimised number of trucks allocated to each individual shovel.

3.2. Flexible Allocation

The results of investigations conducted by the researchers in this field have indicated that a fixed allocation method is not useful and efficient for programming the transportation in large mines. For the purpose of this method, the trucks will not be allocated to a particular shovel throughout the shift, but they are dispatched to the shovels at a specific time given the current conditions, and based on a unique system. The studies conducted by other researchers indicate that allocation and dispatching of trucks on a flexible basis can cause their complicated programming and controlling problems to be eliminated; consequently the capacity of loading and transportation of Shovel-Truck systems may be improved considerably.

4. Computer-based Dispatching

Generally speaking, maximising the production volume of the mine using available equipment is considered as the main objective of all dispatching systems. To do this and with regard to truck dispatching which is a dynamic and active operation, an algorithm will be required. This algorithm must be developed in such a way that route selection, truck and shovel status for optimised truck allocation can be monitored continuously (L.K. Nenonen et al., 1981).

Today, monitoring and controlling technology applied to a truck and shovel operation has progressed and guidance systems for directing movement of unmanned trucks are under completion. Integration of computer-based dispatching, precise monitoring and movement of unmanned trucks in the future will cause the excessive costs of transportation systems of open pit mines to decline significantly (Kolonja et al., 1993).

Computer-based dispatching can be defined as a dynamic allocation of a specific truck to a specific shovel during the time period of production. Nowadays, truck dispatching has become a necessity for all mines even small open pit operation. By increasing the efficiency of transportation, the costs of production will be generally lowered and computer-based dispatching can become compatibly economical with all open pit mining operations. An algorithm or a procedure used for making a proper decision during truck dispatching is considered as the most important element of a dispatching system. The extent of a mining operation, special objectives, transportation structure, condition of the operators equipment, geological condition (grades and continuity) and financial resources of a mine are the amongst the many factors affecting the choice of a dispatching system. Similarly, the above factors greatly affect the choice of dispatching methods (Kolonja et al., 1993).

The capability of a truck dispatching algorithm to maximise the production and maintain the quality of mineral within a specified range will depend on the truck's instantaneous algorithm and linear and/or non-linear programming models. In addition, the capability of a truck dispatching system to react rapidly towards any unexpected changes in a truck or shovel's position is of a great importance. Target functions usually used in programming a model for truck allocation are: maximisation of truck and shovel productivity, maximisation of production, minimisation of total transportation and minimisation of the number of trucks. For the purpose of instantaneous truck dispatching, mathematical algorithms, innovative algorithms and a combination of these two types have been presented (L.K. Nenonen et al., 1981; Sgurev et al., 1989).

5. The Logic Applied for Developing the Algorithm

For the purpose of presenting a real-time dispatching model in such a way that the influence of say a difference in truck capacity in a mine's transportation fleet is observed, an algorithm has been developed. This algorithm consists of two stages. The first stage is based on Network Flow Theory. Through a Network Analysis technique, the best route between the intended departure point and destination point is determined taking into account all of the possible transportation routes between the nodes. Then, given the designated routes, the truck allocation is accomplished according to a mathematical method of integer programming, as if all operational and equipment constraints have been taken into consideration, and then optimised allocation of trucks with different capacities under circumstances of real-time as well as computer-based dispatching is met.

As mentioned before, this two-stage algorithm approach is based on programming methods and is compatible with truck computer-based dispatching.

5.1. The Best Route Model

By considering a network where the length of its branches is non-negative and known, the concept of the best route based on the shortest route in such a network means finding the shortest distance between starting point and destination. One of the most efficient algorithms in this connection is given as follows:

- Intention of "n" repetition: The n^{th} node closed to starting point is specified. (This operation is repeated for $n = 1, 2, 3, \dots$ till it arrives at the destination).
- Input information for the n^{th} repetition: At the n^{th} repetition, information (data) on $n - 1$ nodes which are closer to the starting point (and are obtained during the previous repetition) will be required. These data include the shortest route as well as the distance of these nodes from the starting point. These nodes and the starting point are called solved nodes and the other nodes are called unsolved nodes.
- Those nodes can be selected as the n^{th} node close to the starting point: Each individual unsolved node which closer to one of the solved nodes may be selected as the n^{th} node close to the starting point.
- Calculation of the n^{th} node close to the starting point: The distance of each node which can be selected as the n^{th} node close to the starting point, consists of the sum of the distances of that node from the solved node plus the shortest distance of that solved node from the starting point. Among all selectable nodes, the node whose distance from the starting point is the closest distance will be selected.

Generally, programming based on Network Theory is comparable with the basic structure of dynamic programming. Wherever a series of interrelated decisions is required, then dynamic programming, which is naturally a mathematical method will be applied frequently. A dynamic programming form uses a system-oriented process and determines a combination of sequential decisions which finally causes the total efficiency of an operation to be maximised.

The issues found in dynamic programming can be compared to that found in Network Theory. Each individual node represents a state and the network consists of columns of nodes. Each individual node is considered as one stage, so that the flow can run from one node towards the next one. Each individual branch which interconnects two nodes is designated by a digit which can be interpreted as the increase of target function in terms of movement from a state within one stage toward a state within the next stage. By considering such interpretation, it can be seen that a dynamic programming model intends to find the shortest route existing within the network.

5.2. Integer Programming Model

With respect to many of the real problems, if the values excepting an integer are applied to the decision variables, the result will be meaningless. If during formulation of a problem, there is an integer constraint, it is called integer programming.

By eliminating divisibility, we realise the diverse nature of integer programming. One of the most important applications of integer programming is dealing with yes or no decisions. In such cases, we have only two options.

Such decisions (i.e. Yes or No decisions) can be expressed in terms of variables in which two values, i.e. 0 and 1 are selected. Therefore, the j^{th} decision value of yes or no type is represented by x_j. So that if j decision is a Yes decision or if j decision is a No decision, then the values of 1 and 0 will be allocated to them, respectively. These variables are called binary variables or 0 and 1 variables. As a result, any integer programming consisting of only such variables called 0 and 1 would be referred to as Binary Integer Programming.

As mentioned earlier, the calculation complexity of the integer programming method depends on the structure of the case and the number of integer variables. However, the number of constraints is also important but it is of less significance compared with the two above-mentioned factors. In fact, the increase of constraints causes the complexity of calculations to be decreased, due to the decreasing number of justified answers.

6. Information Required for Trucks with Different Capacities

Efficient models of real-time truck dispatching as applied to an open pit mine should have the capability to reach an intelligent allocation through initial data under any circumstance. The most important discrepancy of initial data required for trucks with different capacities that may result from an influential dispatching system is as follows:

The difference in the capacity may give rise to a difference in the dimensions and weight of a truck which must be considered for comparing against the roads' condition (i.e. width, gradient and radius,) and the distances of transportation. Usually, differences in the capacity may give rise to differences in power and traction of the trucks and for this reason, transportation intervals between the shovels discharging points must be considered and the technical specifications of the trucks such as minimum, maximum and average movement velocity with and without load, maneuvering power, turning radius and braking efficiency have to be compared. It is clear that any difference in a trucks capacity may cause the loading time by a shovel to be varied. Those trucks with higher capacities require more discharge time at the dumping location than those ones with lower capacities hence the discharging time required for trucks' with different capacities will be varied.

With regard to the stripping ratio, any difference in transportation capacity of the trucks may cause changes in the stripping ratio during the fixed period of time. Any differences in transportation capacities of the trucks may naturally give a difference in the overall costs.

7. A Real-time Dispatching Model for Trucks with Different Capacities

As mentioned previously, the best route model has been used for the optimised determination of routes between departure and destination points. To do this, information on the mine as well as the routes are required. Information about the ore bench faces, waste bench faces, ore and waste dumps, the crushers and local positions between them are among the most important information. Topography of the mine site and existing elevation differences are also of a great significance. The most important information required for the roads are the possible routes between face bench locations as mentioned above, intersections and communicative nodes existing within the possible routes and the slope of the respective routes. Therefore, the time period spent by each individual unloaded and loaded truck can be calculated for each type of truck (with different capacities and specifications). This information, as the input data of the best route model are used and the related output consists of optimised routes between each departure and destination and the time spent by each type of truck for each of the determined routes. The algorithm presented at this stage is depicted below in figure 1.

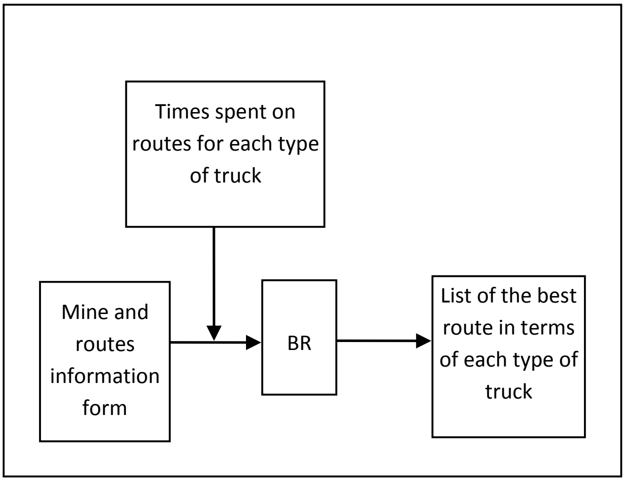

Fig. 1. Best route determination algorithm

When the best transportation routes are selected, truck allocation will be accomplished using a Binary Integer Programming (BIP) model. The algorithm of this model was developed based on minimising the function of the total cost of loading and transportation. Defined target functions will be optimised by the BIP model considering the following constraints:

1. Flow continuity in loading and unloading points;
2. Allocation time;
3. Total number of current trucks;
4. Maximum capacity of unloading points;
5. Maximum loading of each shovel;
6. Volume of production;
7. Stripping ratio according to production schedule;
8. Grade required in blending process.

So, given the above-mentioned constraints which are totally dependent on the design of the mine and mining planning and by solving the BIP model, real-time allocation of trucks with different capacities can be accomplished. This research has given rise to developing a model that its target function is defined as equation (1):

$$
\begin{aligned}
&MIN: \sum_{i=1}^{i=N_t} \sum_{j=1}^{j=N_n} CE_{ijkl}.X_{ijkl} + \sum_{i=1}^{i=N_t} \sum_{j=1}^{j=N_n} CL_{ijkl}.Y_{ijkl} \\
&+ \sum_{n=1}^{n=N_s} CS_n (SC_n - \sum_{i=1}^{i=N_t} \sum_{j=1}^{j=N_n} TC_i . X_{ijkl}) \\
&+ \sum_{m=1}^{m=N_s} CC_m (C_m - \sum_{i=1}^{i=N_t} \sum_{j=1}^{j=N_n} TC_{ii} . Y_{ijkl}) \\
&+ \sum_{p=1}^{p=N_s} CR_p (\sum_{i=1}^{i=N_t} \sum_{j=1}^{j=N_n} Y_{ijkl}) \\
&\text{for } (k,l) \in R
\end{aligned}
\tag{1}
$$

In which:

CE_{ijkl} — cost of transportation of unloaded truck of i type and number of j from starting point of k to destination of l.
X_{ijkl} — unloaded truck of i type and number of j from starting point of k to destination of l (Unknown).
N_t — number of all kinds of trucks in terms of capacity.
CL_{ijkl} — cost of transportation of loaded truck of i type and number of j from starting point of k to destination of l.
Y_{ijkl} — loaded truck of i type and number of j from starting point of k to destination of l (Unknown).
CS_n — cost of each tonne of remained capacity of n^{th} shovel.
SC_n — loading capacity of n^{th} shovel.
TC_i — capacity of the truck of type i.
N_s — number of shovels loading.
CC_m — cost of each tonne of remained capacity of n^{th} crusher.
C_m — maximum capacity of a working crusher.
N_c — numbers of working crushers.
CR_p — cost of reloading of ores from p^{th} depot.
R — possible routes between loading and discharging points.
N_p — number of ores' depot.

In order to maintain the continuity of loading and transportation flow, the numbers of each type of truck arriving at the loading point must be equal to the number of the trucks going out from the loading point. So, this requirement has been taken into consideration as shown in equation (2):

$$
\begin{aligned}
&\sum_{k=1}^{k=N_k} X_{ijkl} - \sum_{l=1}^{k=N_l} Y_{ijkl} = 0 \\
&\text{for } i = 1,2,\ldots,N_t\,,\ j = 1,2,\ldots,N_n
\end{aligned}
\tag{2}
$$

In which:

N_k — number of possible routes through which the trucks can arrive at loading point of l after they depart from discharging point of k.

N_l — number of possible routes through which the trucks can exit discharging point of l after they depart from loading point of k.

For the purpose of observing the appropriate allocation time, the sum of a time series of allocation of each truck must be less than the time period taken for truck allocation in each stage of real-time dispatching. So, this requirement is defined as equation (3):

$$\begin{aligned} &\sum_{k=1}^{k=N_k} \sum_{l=1}^{l=N_l} (ET_{ijkl} + PET_{ijkl}) X_{ijkl} + \\ &\sum_{k=1}^{k=N_k} \sum_{l=1}^{l=N_l} (LT_{ijkl} + PLT_{ijkl}) Y_{ijkl} \le t \\ &\text{for } i = 1,\dots,N_t\,,\ j = 1,\dots,N_n \end{aligned} \tag{3}$$

In which:

ET_{ijkl} — travelling time of unloaded truck of i type and number of j from starting point of k to destination of l.

PET_{ijkl} — remaining travelling time of unloaded truck of i type and number of j from starting point of k to destination of l.

LT_{ijkl} — travelling time of loaded truck of i type and number of j from starting point of k to destination of l.

PLT_{ijkl} — remaining travelling time of loaded truck of i type and number of j from starting point of k to destination of l.

t — period of allocation or duration of period.

It is worthy to note that as lower as value of t is, the higher is its accuracy. Therefore, the least time period for t has to be equal to the longest travelling time between departure point of k and destination of l.

Since the number of ready-to-work trucks may be changed over time, the following equation (equation 4) may cause an appropriate relationship to be established between available trucks with a volume of transportation:

$$\begin{aligned} &\sum_{j=1}^{j=N_n} X_{ijkl} + \sum_{j=1}^{j=N_n} Y_{ijkl} \le N, \\ &\text{for } i = 1,\dots,N_t\,,\ (k,l) \in R \end{aligned} \tag{4}$$

In which:

N — number of ready-to-work trucks.

In order to reach the maximum capacity of discharging points while observing reception capacity of such places, the following equation is considered:

$$\sum_{i=1}^{i=N_t} \sum_{j=1}^{j=N_n} TC_i \, . Y_{ijkl} \leq D_m, \quad \text{for}, \forall l = m, \ (k,l) \in R \tag{5}$$

In which:

D_m — maximum capacity of m^{th} discharging point during accomplishment of the model.

In order to reach the maximum loading capacity of shovels, the following equation has to be applied:

$$\sum_{i=1}^{i=N_t} \sum_{j=1}^{j=N_n} TC_i \, . Y_{ijkl} \leq SC_n, \quad \text{for}, \forall l = n \ , \ (k,l) \in R \tag{6}$$

In which:

SC_n — maximum capacity of n^{th} shovel during accomplishment of the model.

The trucks have to be dispatched so that the requirement of a desired volume of production at the mine is met and optimised as best possible. To do this, equation (7) is considered:

$$\sum_{i=1}^{i=N_t} \sum_{j=1}^{j=N_n} TC_i \, . Y_{ijkl} \geq P_t \tag{7}$$

In which:

P_t — minimum volume of ore desired for period of allocation.

By applying the following equation, the stripping ratio is set to:

$$\sum_{i=1}^{i=N_t} \sum_{j=1}^{j=N_n} TC_i \, . Y_{ijkl} \geq SR \, . P_t \tag{8}$$

In which:

SR — stripping ratio according to production schedule.

In order to reach a proper blending condition for each ore in proportion to their respective each mill, the following equations are considered as equation No 9 and 10 respectively:

$$\sum_{i=1}^{i=N_t} \sum_{j=1}^{j=N_n} TC_i \, . Y_{ijkl} (UG_{pm} - G_{ijp}) / (\sum_{i=1}^{i=N_t} \sum_{j=1}^{j=N_n} TC_i \, . Y_{ijkl}) \geq 0 \tag{9}$$

$$\sum_{i=1}^{i=N_t} \sum_{j=1}^{j=N_n} TC_i \, . Y_{ijkl} (G_{ijp} - LG_{ipm}) / (\sum_{i=1}^{i=N_t} \sum_{j=1}^{j=N_n} TC_i \, . Y_{ijkl}) \geq 0 \tag{10}$$

In which:

UG_{pm} — upper limit of p^{th} ore grade for m^{th} mill.
G_{ijp} — mean value of p^{th} ore grade related to truck of i type and number of j.
LG_{pm} — lower limit of p^{th} *ore* grade for m^{th} mill.

8. Conclusion

Given the excessive cost of transportation in open pit mines as well as some of the inappropriate truck dispatching systems for the purpose of minimising the total cost of loading and transportation, placing into operation an advanced and suitable truck dispatching system causes the respective costs to be lowered significantly and as a result the profitability of the operation to be improved. The experiences acquired during these investigations has shown that putting into operation a flexible dispatching system into a mining operation causes the volume of production to be increased and hence the number of loading facilities and trucks needed for reaching a targeted rate of production to be decreased.

One of the features of the designed model as presented in this paper is its capability to optimise the mines' transportation system using integer programming. Simplicity and precision are two major merits of such a model. Another advantage of this model is the possibility of using several types of trucks with different capacities within the transportation fleet.

This model may be used in mines where their processing plant utilises several production lines. In other words, by using this model, it is practical that ores with different grades can be transferred and moved to several crushers for blending purposes.

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